

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

JSC-10607
Supplement 1

SUMMARY OF LIGHTNING ACTIVITIES
BY NASA FOR THE
APOLLO SOYUZ TEST PROJECT

SUPPLEMENT NO. 1
TO
APOLLO SOYUZ MISSION EVALUATION REPORT

(NASA-TM-74755) SUMMARY OF LIGHTNING
ACTIVITIES BY NASA FOR THE APOLLO SOYUZ TEST
PROJECT: SUPPLEMENT NO. 1 TO APOLLO SOYUZ
MISSION EVALUATION REPORT (NASA) 38 p
HC A03/MF A01

N77-26729

Unclas
CSCL 04A G3/46 37057



National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER

Houston, Texas
July 1976

SUMMARY OF LIGHTNING ACTIVITIES BY NASA
FOR THE
APOLLO SOYUZ TEST PROJECT

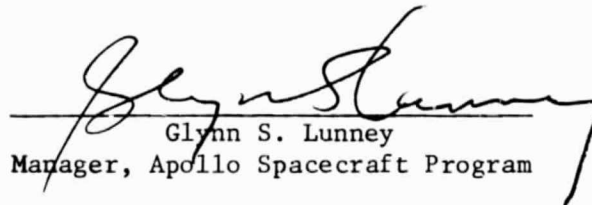
Supplement No. 1
to
Apollo Soyuz Mission Evaluation Report

PREPARED BY

Mission Evaluation Team

APPROVED BY


Donald D. Arabian
Manager, Program Operations Office


Glynn S. Lunney
Manager, Apollo Spacecraft Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS
July 1976

CONTENTS

Section	Page
INTRODUCTION	1
LIGHTNING RELATED PREPARATIONS FOR THE APOLLO SOYUZ TEST PROJECT MISSION	2
Prelaunch Assessment	2
Launch Day Aircraft Operations	9
Conclusions	9
POST APOLLO SOYUZ TEST PROJECT ACTIVITIES	11
Viking Spacecraft Launch	11
Cloud Electrification Studies	11
APPENDIX A - HISTORY OF MANNED SPACE VEHICLE INVOLVEMENT WITH LIGHTNING	A-1
APPENDIX B - LIGHTNING INSTRUMENTATION SYSTEMS AT KSC	B-1
APPENDIX C - MEASUREMENT OF ELECTRIC FIELDS FROM AIRCRAFT	C-1

INTRODUCTION

The Apollo Soyuz Test Project launch was scheduled for approximately 3 o'clock e.d.t. on the afternoon of July 15, 1975, the time of the statistical peak of thunderstorm activity at the Kennedy Space Center (KSC). The launch window for the Apollo launch was unusually short (5 to 8 minutes). Any hold for weather would force the postponement of the launch until the next day. Since the existing launch rules were based primarily on meteorological observations, the presence of a nearby storm could cause the postponement of the launch even though the electric field intensity along the track of the vehicle was sufficiently low that triggering of lightning by the launch vehicle could not occur.

To avoid the possibility of an unnecessary launch delay, NASA initiated a special program to provide aircraft measurements of electric fields at various altitudes over the Apollo vehicle launch pad. Eight aircraft, each equipped with electric field meters, were used in the program. This report discusses this program and some of the more important findings. Also included is a summary of the history of manned space vehicle involvement with lightning (appendix A), a brief description of the lightning instrumentation in use at KSC at the time of the Apollo Soyuz mission (appendix B), and a discussion of the airborne instrumentation and related data (appendix C).

LIGHTNING RELATED PREPARATIONS FOR THE APOLLO SOYUZ TEST PROJECT MISSION

Prelaunch Assessment

During the year preceding the Apollo Soyuz Test Project mission, it became evident that the launch would occur during the period of highest thunderstorm incidence at KSC (fig. 1). Consequently, simulated lightning tests were performed on a non-flight launch vehicle and the backup spacecraft to assess the damage that could be caused by lightning. The results of these tests indicated that the vehicle could be lost if it experienced an inflight lightning strike. Because of this hazard and in light of the past experiences with lightning (appendix A), the existing launch rules (fig. 2) were reexamined to determine if tighter restrictions should be imposed. This activity, however, indicated quite the opposite. It was found that the restrictions could, in fact, be relaxed if certain conditions were met. Prior experience indicated that the risk of triggering lightning during launch would be low if the electric field intensities measured by the ground instrumentation did not exceed 1000 volts per meter and if the electric field intensities along the vehicle flight path did not exceed 3000 volts per meter to 15 000 volts per meter.

In the past, the weather office at KSC used electric field intensity measurements from a large network of field mills (see appendix B for a description of field mills and the network) to identify impending lightning hazards to space vehicles. Very little data were available to correlate the field intensities aloft to those measured at ground level. A special research program was conducted by KSC and the National Oceanic and Atmospheric Administration (NOAA) to obtain simultaneous ground and airborne field intensity measurements. Four aircraft participated in this effort. (See table I for the aircraft types and appendix C for a discussion of a typical airborne system.) The results of the KSC/NOAA research activity indicated that, below an altitude of 3050 meters, the airborne data compared favorably with the data obtained using ground instrumentation. Above this altitude, however, the ground-based instrumentation could not be relied upon to provide an accurate measurement of the electric field intensities aloft. The conclusion was that airborne electric field data would be required in support of the Apollo launch.

In order to measure field levels along the complete track of the launch vehicle, four additional high-altitude aircraft were obtained and equipped with electric field meters. Thus, on launch day, eight aircraft would be available for data acquisition at different altitudes just before the Apollo lift-off (fig. 3). In conjunction with ground readings, the data from these aircraft would be used to implement a set of revised launch rules that were based on acceptable/unacceptable risk factors associated with real-time measurement of electric field intensities (figs. 4 and 5). With this approach, it would be possible to launch safely even though electrified clouds were in the launch vicinity.

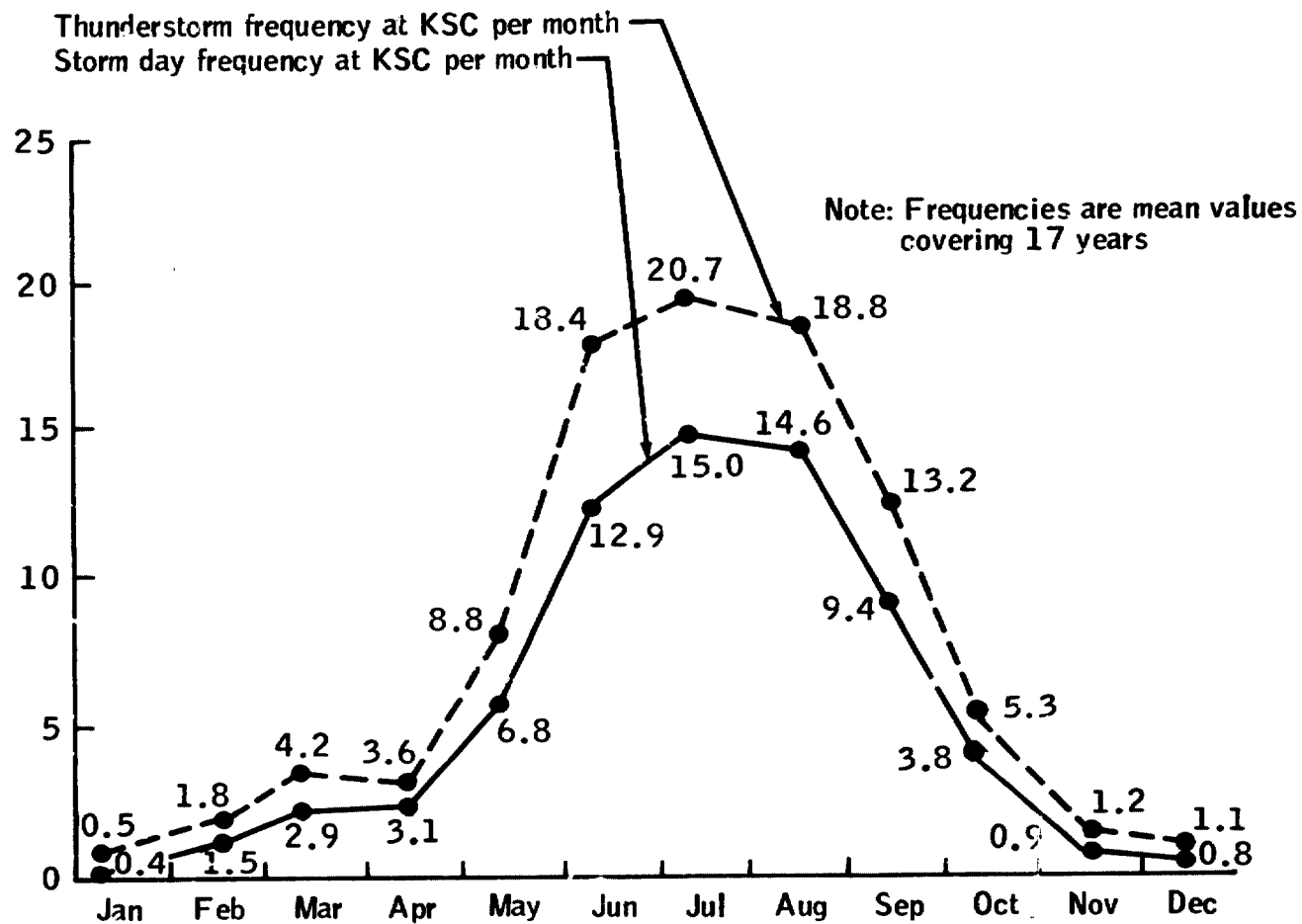


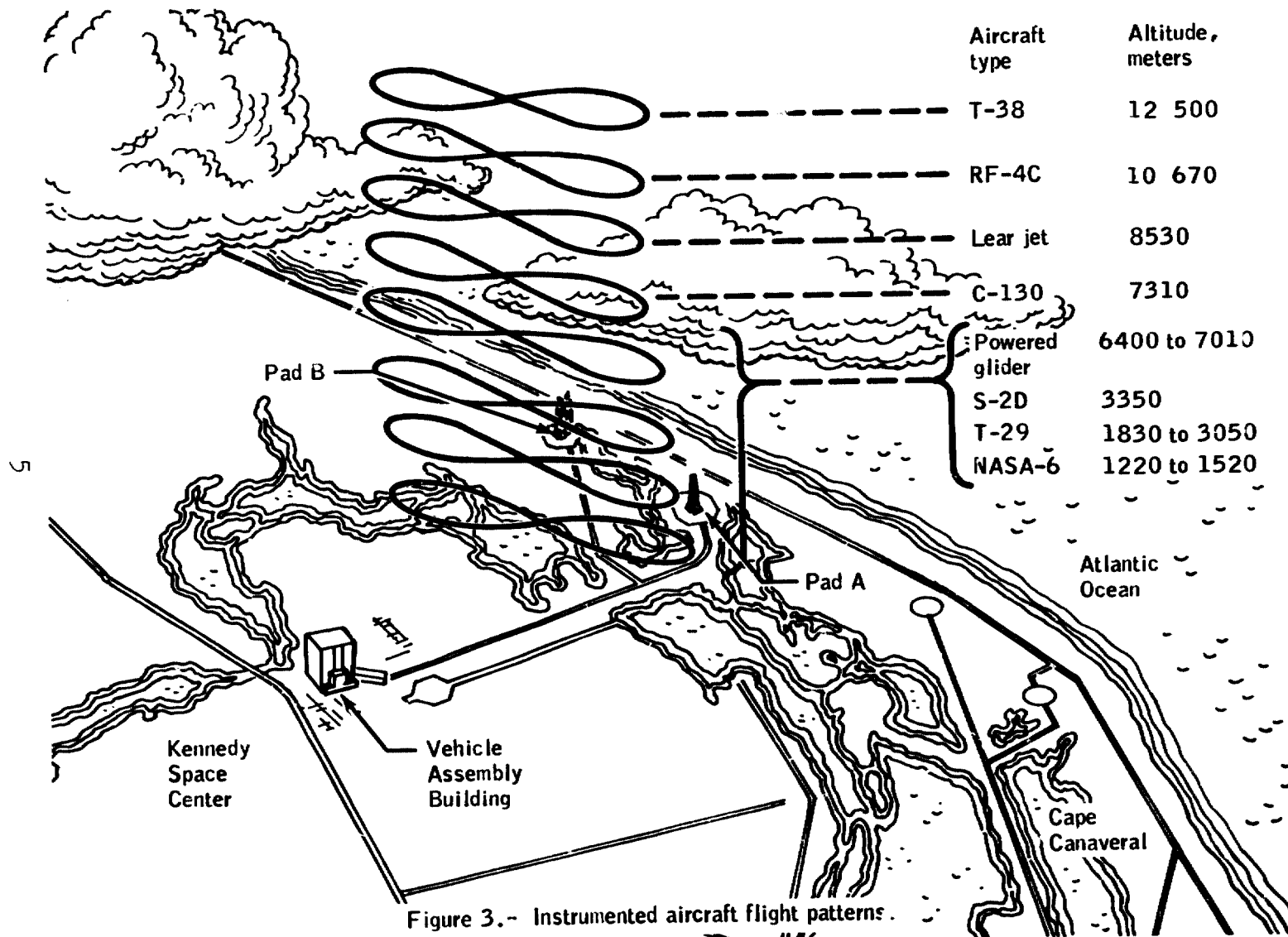
Figure 1.- Lightning history at KSC

SEVERE WEATHER CONDITIONS

LAUNCH RULES:

1. THE SPACE VEHICLE WILL NOT BE LAUNCHED IF THE NOMINAL FLIGHT PATH WILL CARRY THE VEHICLE:
 - A. WITHIN 5 STATUTE MILES OF A CUMULONIBUS (THUNDERSTORM) CLOUD OR WITHIN 3 STATUTE MILES OF AN ASSOCIATED ANVIL.
 - B. THROUGH COLD-FRONT OR SQUALL-LINE CLOUDS WHICH EXTEND ABOVE 10,000 FEET.
 - C. THROUGH MIDDLE CLOUD LAYERS 6,000 FEET OR GREATER IN DEPTH WHERE THE FREEZE LEVEL IS IN THE CLOUDS.
 - D. THROUGH CUMULUS CLOUDS WITH TOPS AT 10,000 FEET OR HIGHER.

Figure 2.- Launch mission rules for Skylab



JOHN F. KENNEDY SPACE CENTER, NASA - LAUNCH MISSION RULES

REV	ITEM	DESCRIPTION			
		<u>WEATHER RESTRICTIONS (CONTINUED):</u>			
3	1-406	<u>SEVERE WEATHER CONDITIONS:</u> 1. THE SPACE VEHICLE WILL NOT BE LAUNCHED IF THE NOMINAL FLIGHT PATH WILL CARRY THE VEHICLE: A. THROUGH A CUMULONIMBUS (THUNDERSTORM) CLOUD. B. WITHIN 5 STATUTE MILES OF A CUMULONIMBUS (THUNDERSTORM) CLOUD OR WITHIN 3 STATUTE MILES OF AN ASSOCIATED ANVIL. THIS RULE MAY BE RELAXED AT THE DISCRETION OF THE LAUNCH DIRECTOR IF THE ELECTRIC FIELD AT THE LAUNCH PAD IS LESS THAN 1 KILOVOLT PER METER. C. THROUGH COLD-FRONT OR SQUALL-LINE CLOUDS WHICH EXTEND ABOVE 10,000 FEET. D. THROUGH MIDDLE CLOUD LAYERS 6,000 FEET OR GREATER IN DEPTH WHERE THE FREEZE LEVEL IS IN THE CLOUDS. E. THROUGH CUMULUS CLOUDS WITH THE FREEZE LEVEL IN THE CLOUDS. F. RULES C, D, AND E ABOVE MAY BE RELAXED AT THE DISCRETION OF THE LAUNCH DIRECTOR WHEN ELECTRIC FIELD MEASUREMENTS IN THE LAUNCH PAD AREA ARE STABLE AND MEASURE LESS THAN 1 KILOVOLT PER METER. G. RULES C, D, AND E ABOVE MAY BE FURTHER RELAXED PROVIDED THAT AIRBORNE AND GROUND ELECTRIC FIELD MEASUREMENTS MEET THE CRITERIA DEFINED IN FIGURE 1. 2. FOR FLIGHT CREW EGRESS RULES RELATIVE TO SEVERE WEATHER CONDITIONS, SEE "FLIGHT CREW SAFETY RULES" SUBSECTION, ITEMS 1-609 (9) AND 1-610 (6).			
	1-407	<u>PAD OR LAUNCH ABORT RECOVERY WEATHER CONDITIONS:</u> THE LAUNCH OPERATIONS MANAGER WILL OBTAIN A GO/NO-GO DECISION FROM THE FLIGHT DIRECTOR BASED UPON THE PAD OR LAUNCH ABORT RECOVERY WEATHER CONDITIONS.			
MISSION	SECTION	STAGE SUBSECTION	SYSTEM	CHANGE NO	PAGE
ASTP	SPACE VEHICLE	WEATHER RESTRICTIONS		JULY 14, 1975	1-18

NSC FORM 4-67A REV 1-75

Figure 4.- Launch mission rules for launching during severe weather.

JOHN F. KENNEDY SPACE CENTER, NASA - LAUNCH MISSION RULES

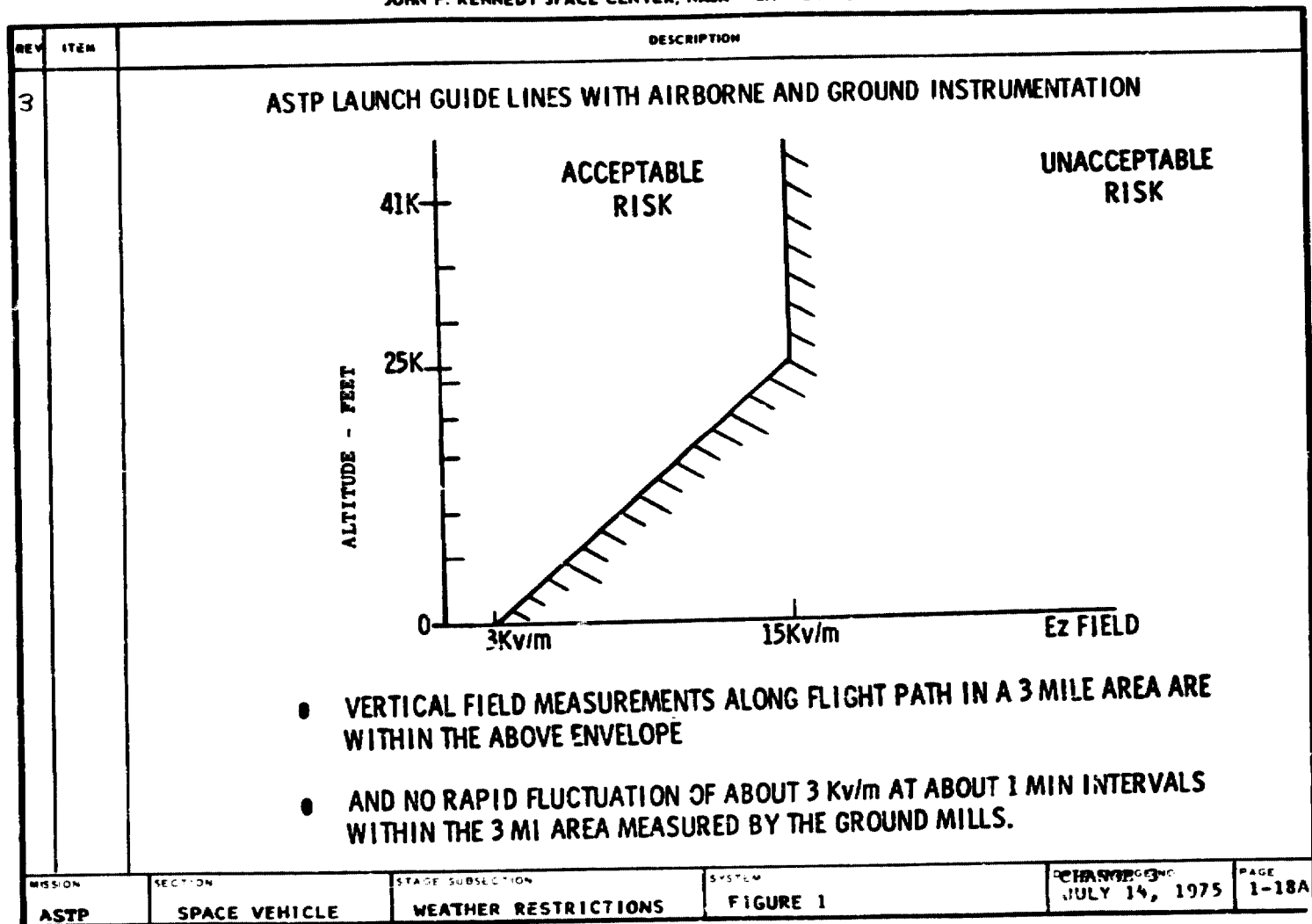


Figure 5.- Launch guidelines with airborne and ground instrumentation.

TABLE 1.- INSTRUMENTED AIRCRAFT

Type of aircraft	NASA or other designation	Remarks
Aircraft for KSC/NOAA research:		
Schweitzer powered glider	---	Owned by U.S. Navy, bailed to New Mexico Tech and based at Socorro, New Mexico.
T-29	---	NOAA aircraft.
S-2D	---	Naval Research Laboratory aircraft under contract to KSC and NOAA.
C-45	NASA 6	KSC aircraft stationed at Patrick AFB. Used as basis for comparison of data.
Additional aircraft for launch vehicle flight path measurements:		
Lear Jet	NASA 705	Ames Research Center aircraft stationed at Moffitt Field, Calif. Instrumented by the Stanford Research Institute.
T-38	NASA 902	JSC aircraft stationed at Ellington AFB. Instrumented by the Stanford Research Institute.
C-130	MIKE 70	U.S. Air Force aircraft stationed at Kirtland AFB. Instrumented by the Air Force Cambridge Research Laboratory.
RF-4C	AGAR 22	U.S. Air Force aircraft stationed at Kirtland AFB. Instrumented by the Air Force Weapons Laboratory.

Launch Day Aircraft Operations

The planned launch time for the Apollo vehicle was 15:50:00 e.d.t., July 15, 1975. A KSC Operations Task Team had been formed to control the aircraft that would fly over the pad area. This area was designated R-2902 as shown in figure 6. The aircraft were scheduled to arrive on station in area R-2902 at T minus 35 minutes with a planned departure at T minus 5 minutes.

The four lower aircraft (fig. 3) were to relay data directly to the KSC weather office while the data acquisition point for the higher aircraft was to be the Range Control Center of the Air Force Eastern Test Range. At the Range Control Center, the data were to be plotted and analyzed by a weather specialist and subsequently transmitted to the KSC weather office. The KSC weather office would then compile the data from all of the aircraft and the ground instrumentation. These data would form the basis to implement the revised launch mission rules for lightning.

Because of the number of aircraft planned to be in the R-2902 area on launch day, prime importance was to be placed on safety and weather avoidance. The Federal Aviation Agency would participate in the planning of aircraft control and safety. All aircraft were to be under the control of the Miami Center and aircraft positions were to be monitored. The aircraft were to enter and depart the R-2902 area from predetermined staging areas controlled by the Range Control Center. In addition, weather advisories were to be relayed to the aircraft on a periodic basis so that the flight patterns could be changed to avoid unsafe weather conditions.

The entire operation went quite smoothly on launch day due mainly to the sequence of weather events leading up to the actual launch time. The deep southwesterly flow pattern that is strongly conducive to afternoon thunderstorm development over the Cape Canaveral area had previously existed, but had ended the day before launch. A change in direction of the upper winds caused a drastic decrease in thunderstorm probability (the probability was 22 percent). Thus, on launch day, conditions were good with scattered cumulus and thin cirrus clouds at the launch site. Thunderstorms were visible to the west and some isolated cumulonimbus clouds were off shore. As a precaution however, the field measuring aircraft were deployed about an hour before launch. After confirming the presence of normal electric fields (fair weather values are 200 volts per meter to 300 volts per meter), the aircraft were released before the scheduled time for them to clear the area.

Conclusions

The lightning related preparations for the Apollo Soyuz Test Project mission highlighted a number of significant points to be considered for future space programs.

Launch delays due to the presence of clouds in the launch area can be avoided by determination of the electric field intensity in the flight path.

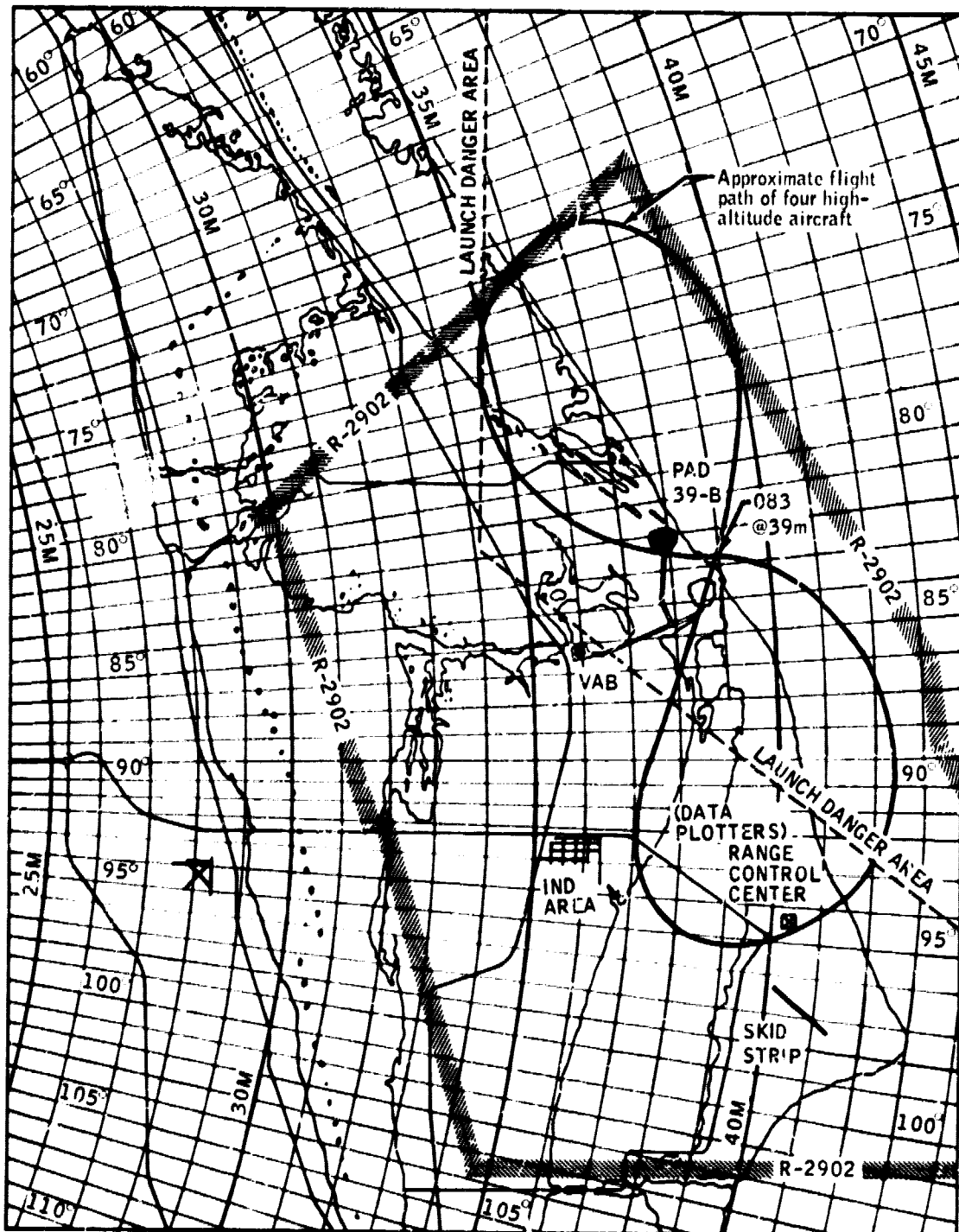


Figure 7. - Area R-2902 and typical flight path.

Further research is required to characterize the electrical properties of various cloud types. This activity should be directed toward reducing the cost and operational complexity of obtaining the electric field intensity data in and near the flight path.

Multiple-instrumented aircraft can be used to measure the electric fields aloft just prior to launch.

Lightning protection should be a major consideration in the design of future vehicles.

POST APOLLO SOYUZ TEST PROJECT ACTIVITIES

Viking Spacecraft Launch

The value of having airborne electric field measuring capability was fully demonstrated in the month following the Apollo Soyuz Test Project mission. Three of the monitoring aircraft supported the two Viking space vehicle launches; one on August 20, 1975, and the other on September 9, 1975.

Since both ground and airborne instrumentation indicated acceptable electric field levels over the launch site, the first vehicle was launched through a thick deck of middle clouds even though the internal cloud temperatures were approaching the freeze level.

For the second launch, large convective storms had developed off shore and were moving toward the launch site. Again, the ground and airborne instrumentation indicated that the electric fields were not dangerously high over the launch site ahead of the storm, and the vehicle was launched through opaque clouds that were estimated to be at an altitude of 2450 meters. Within minutes after launch, these clouds moved on shore and unacceptable high electric fields were present over the launch site.

Neither of these launches would have been permitted without the real-time measurement of electric field intensities aloft.

Cloud Electrification Studies

Of the aircraft that participated in the real-time measurement of electric fields during the Apollo-Soyuz and Viking launches, the Lear Jet had unique capabilities. During one of the prelaunch calibration flights, it was found that the aircraft's 2073-meter-per-minute climb rate made it possible to carry out successive flights over the top of a developing thunderstorm that was growing at a rate of 610 meters per minute.

In recognition of the unique capabilities of the Lear Jet system, provisions were made for it to remain at Patrick Air Force Base following the Apollo-Soyuz launch to make high-altitude field measurements in the vicinity of storm cells over KSC. In particular, a cooperative program was arranged in which the electric fields of cells chosen by NOAA for experiments in seeding with radar chaff were monitored by the Lear Jet. When conditions over KSC were not appropriate for the chaff seeding studies, the Lear Jet was flown around developing thunderstorm cells to study the fields in their vicinity - with particular attention to the region of the anvil. In the course of this flying, electric field data were gathered from ten different storm cells.

Most of the measurements started when a cell was very young. The measurements followed the cell's development throughout the growth period and continued until it began to disintegrate. Photographs or sketches were made of most of the storms studied and the chart records of electric field data were annotated. Accordingly, the data constitutes a unique source of information on the electrical behavior of developing thunderstorms. (See appendix C).

APPENDIX A

HISTORY OF MANNED SPACE VEHICLE INVOLVEMENT WITH LIGHTNING

The Apollo 12 Incident

On November 14, 1969, the Apollo 12 spacecraft was affected by two triggered lightning strikes during launch. Major electrical disturbances were caused at 36.5 seconds and again at 52 seconds. In addition to many temporary effects noted in both the launch vehicle and the spacecraft, some permanent damage resulted - the loss of nine nonessential instrumentation sensors. All upsets and permanent damage were associated with solid-state electrical circuits.

Follow-on investigations determined that the Apollo launch vehicle could, because of its electrical length, trigger lightning if launched through certain electrified cloud configurations. Thus, launch restrictions were imposed to prevent a recurrence of the Apollo 12 incident.

Other Apollo and Skylab Vehicle Lightning Damage

Apollo.- While Apollo 13 and 14 did not experience damage to spacecraft systems or associated ground support equipment, the Apollo 14 launch was delayed for 40 minutes as a result of thunderstorm conditions near the launch site. Prior to the Apollo 15 mission, the launch pad was struck by lightning on five occasions during June and July 1971. Two instrumentation sensors on the spacecraft were damaged on the first occasion and 10 ground support equipment units were damaged during three of the five strikes. Corrective measures were taken to insure proper equipment grounding after the first three strikes and no equipment damage resulted from the last two strikes. The launch facility was hit by lightning twice in March 1973 while the Apollo 16 vehicle was being prepared for launch. Neither the spacecraft nor the ground equipment was affected.

Skylab.- The Skylab 2 spacecraft (CSM 116) experienced damage to four instrumentation sensors in the first of two strikes to the launch facility structure in May 1973. The ground support equipment was not affected. The Skylab 3 spacecraft (CSM 117) was at the launch site in June and July 1973. The first of two strikes to the launch facility resulted in damage to 10 spacecraft instrumentation sensors, 8 ground instrumentation sensors, and 3 ground support equipment units. The Skylab 4 spacecraft (CSM 118) experienced the largest of all the strikes (200 000 amperes) in August 1973. Four spacecraft instrumentation sensors were damaged. In addition, the guidance and navigation system inertial measurement unit, a signal conditioner, and the coupling data unit indicated anomolous operation and were replaced. The ground equipment was not affected.

Lightning Research Activity

As a result of the electrical disturbances experienced during the Apollo 12 launch and the lightning damage to spacecraft and ground equipment on other Apollo missions, the value of further research in this area was recognized. Several experiments were performed prior to, during, and subsequent to the Apollo 13 and Apollo 14 launches to study some of the launch phase electrical phenomena. The Apollo 13 experiments were designed primarily to study the effects of the spacecraft on the atmospheric electrical fields during launch. Other experiments were conducted in connection with Apollo 14 to better define the electrical charge and the triggering mechanism of the discharge. Additional measurements were made subsequent to Apollo 14 to acquire data for the derivation of peak lightning strokes.

Other general lightning research activity was conducted at KSC, including additional measurements to determine parameters of lightning in the launch area, measurement of cloud charge transfer during discharge, stroke characteristics and field changes (magnetic and electric), airborne electric field measurements correlated to ground field measurements, and correlation of cloud charge growth and transfer with associated meteorological phenomena. Also chaff seeding tests were conducted on charged clouds to observe the effect on electric field decay and lightning activity.

APPENDIX B

LIGHTNING INSTRUMENTATION SYSTEMS AT KSC

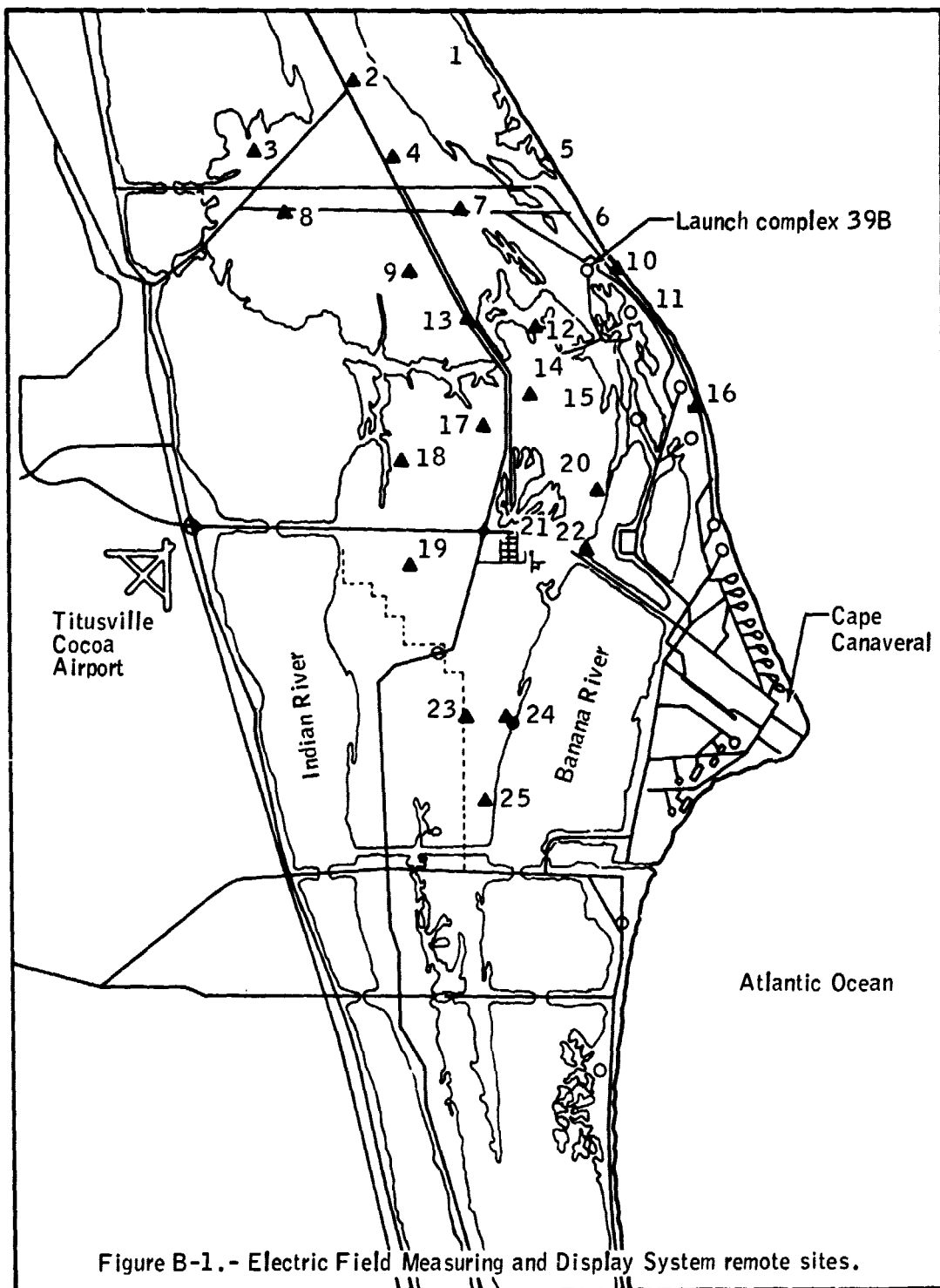
KSC involvement with lightning instrumentation began with the construction of the Saturn mobile launcher and other high structures such as the mobile service structure and the vehicle assembly building. It was necessary to provide advance thunderstorm warning for the safety of outdoor work crews and to initiate measures that would protect any equipment or instruments that could be damaged or destroyed by a direct or nearby lightning strike. In later launch operations, it was necessary to locate and determine the magnitude of lightning strikes so that a proper damage assessment could be made. Thus, a lightning warning instrumentation system and a lightning data acquisition system existed at the time of the Apollo Soyuz mission.

Lightning Warning Instrumentation System

The lightning warning instrumentation system has two major elements - an electric field measuring and display system and an instrumented aircraft. The electric field measuring and display system consists of 25 remote sites (fig. B-1) which measure the electric field of the atmosphere. The field mill is the instrument that is used for detection and measurement of electric fields. "Mill" is jargon for a capacitively coupled electric field pickup or probe and the terminology comes from the fact that the detector has a rotating shutter over the sensing plate (fig. B-2). The grounded rotating plate shutter causes the electric field applied to the sensing plate to fluctuate. This fluctuation generates an a-c signal across the sensing plates which, in turn, is amplified and converted into a voltage that is proportional to the electric field. The range of the field-measuring instruments is plus 15 kilovolts per meter to minus 15 kilovolts per meter with a resolution of 30 volts per meter.

Signals from the individual field mills are digitized and transmitted to a central data processing facility. The entire network of field mill sites is interrogated simultaneously from this data processing area at a once-a-minute rate. After the interrogation signal, each field mill station reports back sequentially to a central receiver system. The computer then generates a page listing of electric field data and a map display showing the equipotential lines of the electric field. The centers of these closed-loop patterns indicate the high-charge centers under the clouds above KSC.

The instrumented aircraft (NASA-6) was obtained to extend the range of electric field measurements and to help determine the relationship of the ground-measured electric field with actual cloud electrification. The instrumentation measures and records the electric field, air temperature, and dew point. Radiometric temperature measurements and photographs are also obtained. The aircraft is especially useful for detecting the initial charge generating stages of clouds approaching the launch area. Electric field values of 10 volts per meter to 800 000 volts per meter can be measured.



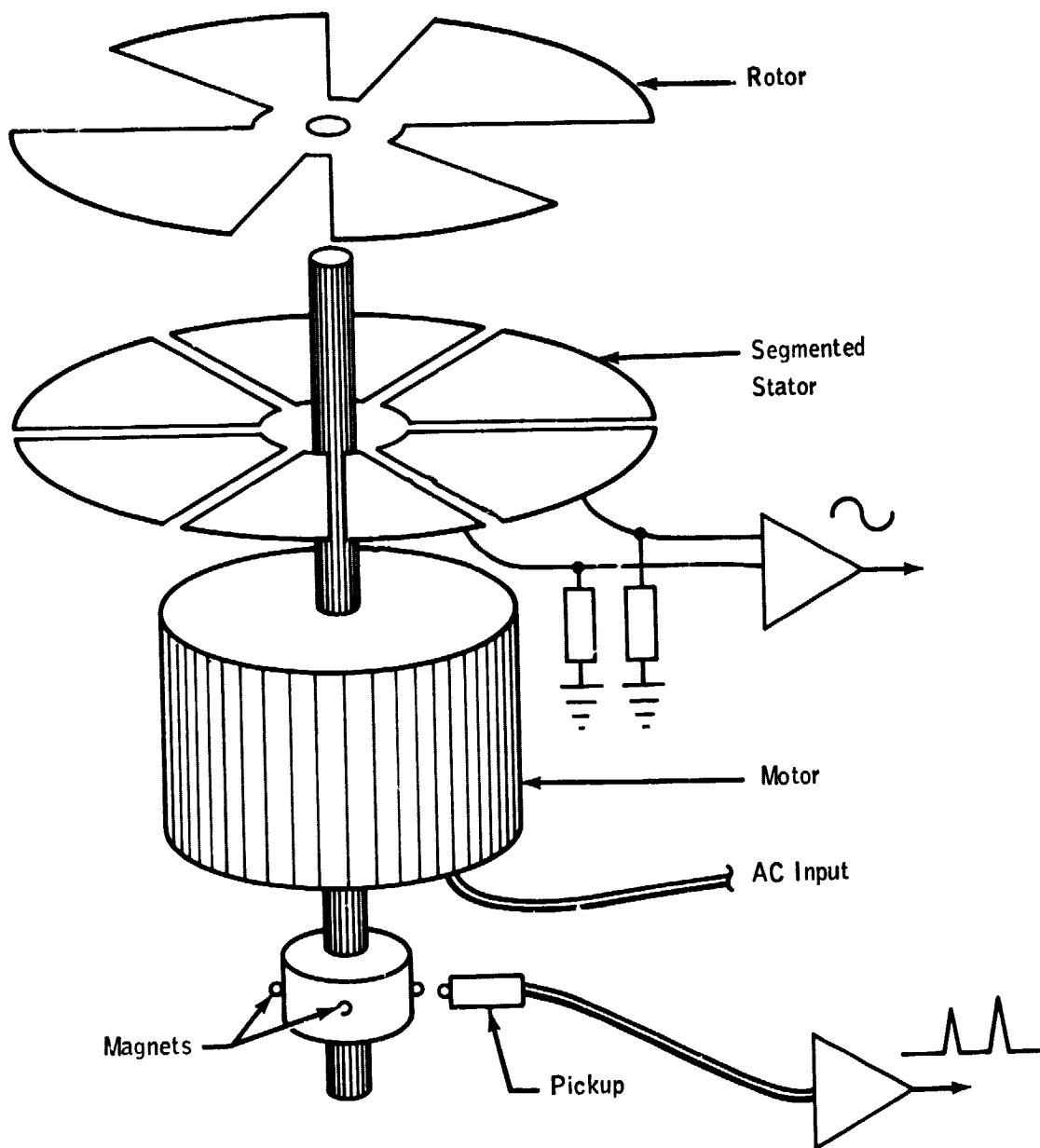


Figure B-2. - Field mill.

The electric field readings obtained with the field mills and the NASA 6 aircraft play an important part in the adverse weather warnings issued by the KSC weather office. For long range monitoring of weather systems at or approaching KSC, two weather surveillance radars are used - an FPS 77 unit with a range of 370 kilometers located at Patrick Air Force Base, and a WSR-57 unit with a range of 460 kilometers located at Daytona Beach, Florida. For local KSC monitoring, a WSR 72X radar with a range of 55 kilometers is used. The display of the FPS 77 radar is available at the KSC weather office through a closed-circuit television loop. The radars are used principally to determine cloud location, size, movement, and rate of growth.

Depending upon these data, and when the field mill readings start increasing above the fair weather values (100 to 300 volts per meter positive) to approximately 2000 volts per meter, conditions exist that are conducive to cloud-to-ground lightning. Adverse weather warnings are issued before the ground field readings exceed 3000 volts per meter. If the clouds are high, then the electrification measured by the ground field mills becomes less reliable and the NASA 6 aircraft is dispatched to measure the electric fields aloft. Large and fluctuating fields aloft are of concern during launch because of the lightning triggering possibility. The NASA 6 aircraft is also used outside the KSC area to monitor developing clouds that are approaching the KSC area.

A research and development Lightning Detection and Ranging System is also being developed for future use. The system operation is based upon measuring the precise time-of-arrival of r-f emission from lightning discharge channels in both azimuth and elevation. The range to the discharge is determined by processing the time-of-arrival with a minicomputer which provides the inputs to transient recorders. These data are then transmitted to remote displays and, thus, provide location of clouds with electrical activity.

Lightning Data Acquisition System

The lightning data acquisition systems for Apollo, Skylab and the Apollo Soyuz Test Project were closely associated with the lightning protection systems of the launch pad structure. There was a lightning mast atop the mobile service structure and, for the Apollo Soyuz Test Project, a special launch tower lightning protection system was installed to protect the mobile launcher. This system consisted of a catenary steel cable that was supported above the mobile launcher by a 25-meter fiberglass tower (fig. B-3). The cable was anchored to earth at two places 275 meters from the structure base. The lightning peak current and the current waveform was measured at the anchor points. The output of a current transformer around the cable grounding wire was fed to a transient recorder which obtained the digital equivalent of electrical waveforms. Currents surging through current transformers located on the ground down wires were transformed into voltages and fed to individual memory voltmeters and recorded on strip charts.

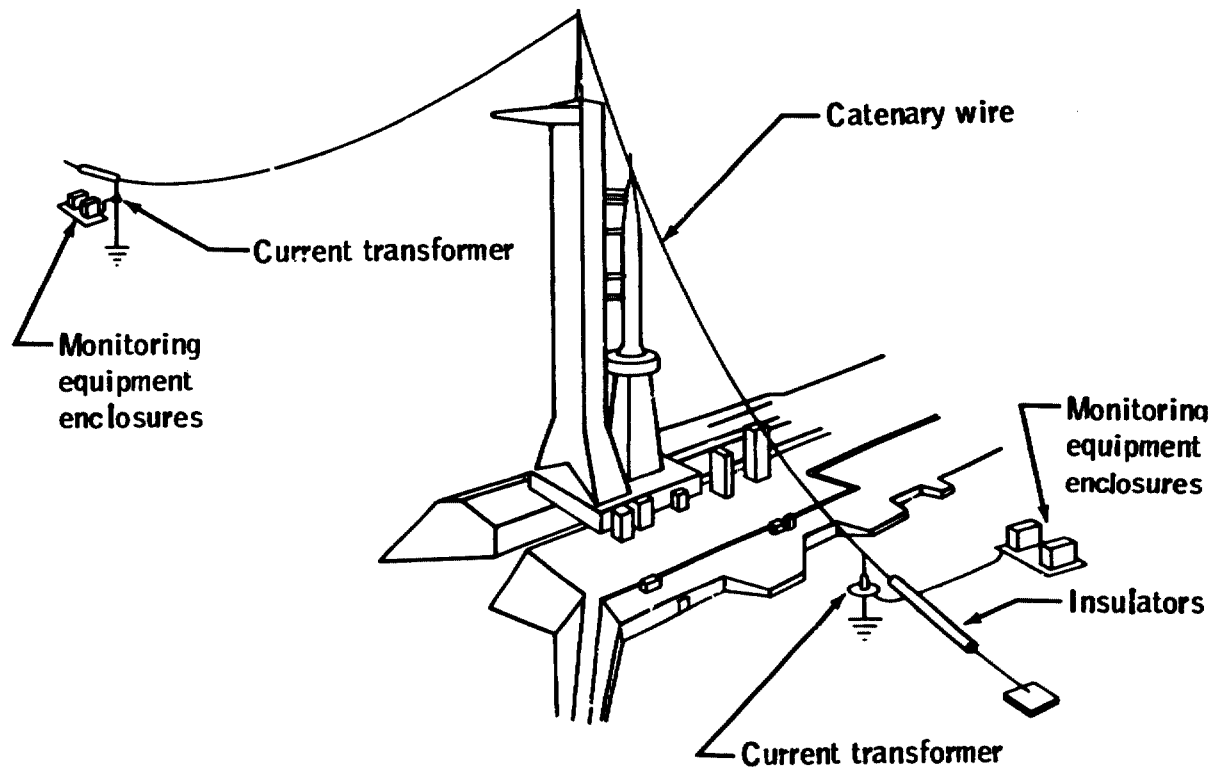


Figure B-3.- Launch Complex Lighting Protection Systems for the Apollo Soyuz Test Project.

The memory voltmeter is a wideband solid-state voltmeter having amplitude memory. This instrument measures voltages ranging from dc to rf, holding the maximum amplitude indications of continuous voltages or spiked transient pulses as short as 50 nanoseconds. The sensed voltage is held in electronic circuitry and indicated on a meter until reset by the operator. Amplitudes greater than those stored cause the indications to increase. The instrument indications are of the maximum amplitude detected between reset periods. This memory voltmeter has an automatic reset circuit that is adjustable over a wide range with an automatic recovery time of 5 seconds arbitrarily selected.

Another method of monitoring lightning strikes to launch-associated structures is by the use of 1.27 by 0.95 cm cobalt alloy laminated slugs. These slugs (called magnetic links) retain residual magnetism induced by the current flow of a nearby lightning strike. The magnetic links were mounted on the highest points of structures and weather towers and on both the high and low ends of the pad slide-wire escape system at Launch Complex 39. When installed, the slide-wire itself acted as the conductor for lightning strikes. Magnetic links were located on wooden arms or masts on each mobile launcher and on the crane cabs. Three magnetic links were inserted in drilled holes on the side of the arm assembly and retained by phenolic tabs. They were mounted 12.7, 25.4 and 60.9 cm from the conducting structure for exposure to magnetic fields generated by lightning strikes (fig. B-4).

The magnetic links are magnetized when lightning strikes the structure near them. The flux density is dependent on the distance of each link from the centerline of the lightning rod, the magnitude of the current induced by the strike, and the magnetic characteristics of that particular batch of links. Residual magnetism in a link is measured with a unigalvanometer. A calibration curve supplied by the manufacturer is then used to convert the unigalvanometer indication to the peak kiloampere current flow in the lightning strike. The properties of the links are such that they can measure currents from 3000 to 100 000 amperes. In the field, an ordinary pocket compass held near each link is enough to determine if a link has been magnetized.

An automatic lightning photography system augments the measurement system. Three cameras around the periphery of the launch area (Complex 39) photograph lightning strikes. Each camera station of the system consists of a motorized Nikon camera with a 180° (fisheye) lens and a triggering circuit as shown in figure B-5. The lens is aimed such that a horizon-to-horizon picture in all directions is obtained. The camera systems are self-contained giving complete freedom of placement. The cameras are routinely serviced once a week with a film load of 250 frames. Camera performance figures include a shutter opening of 40 milliseconds, exposure time of 0.5 second, and a reset interval of 1 second. The electric field pulse from a lightning strike triggers the electronic circuitry, which trips the camera shutter and photographs the lightning. The film then automatically advances and the camera is automatically reset for the next lightning strike. Although the leader lightning strike is not photographed, succeeding strikes which immediately follow the leader's path were photographed. This method permits photographing 90 percent of the cloud-to-ground flashes. The photographs are used to locate the lightning impact point, either by showing actual location or by triangulation.

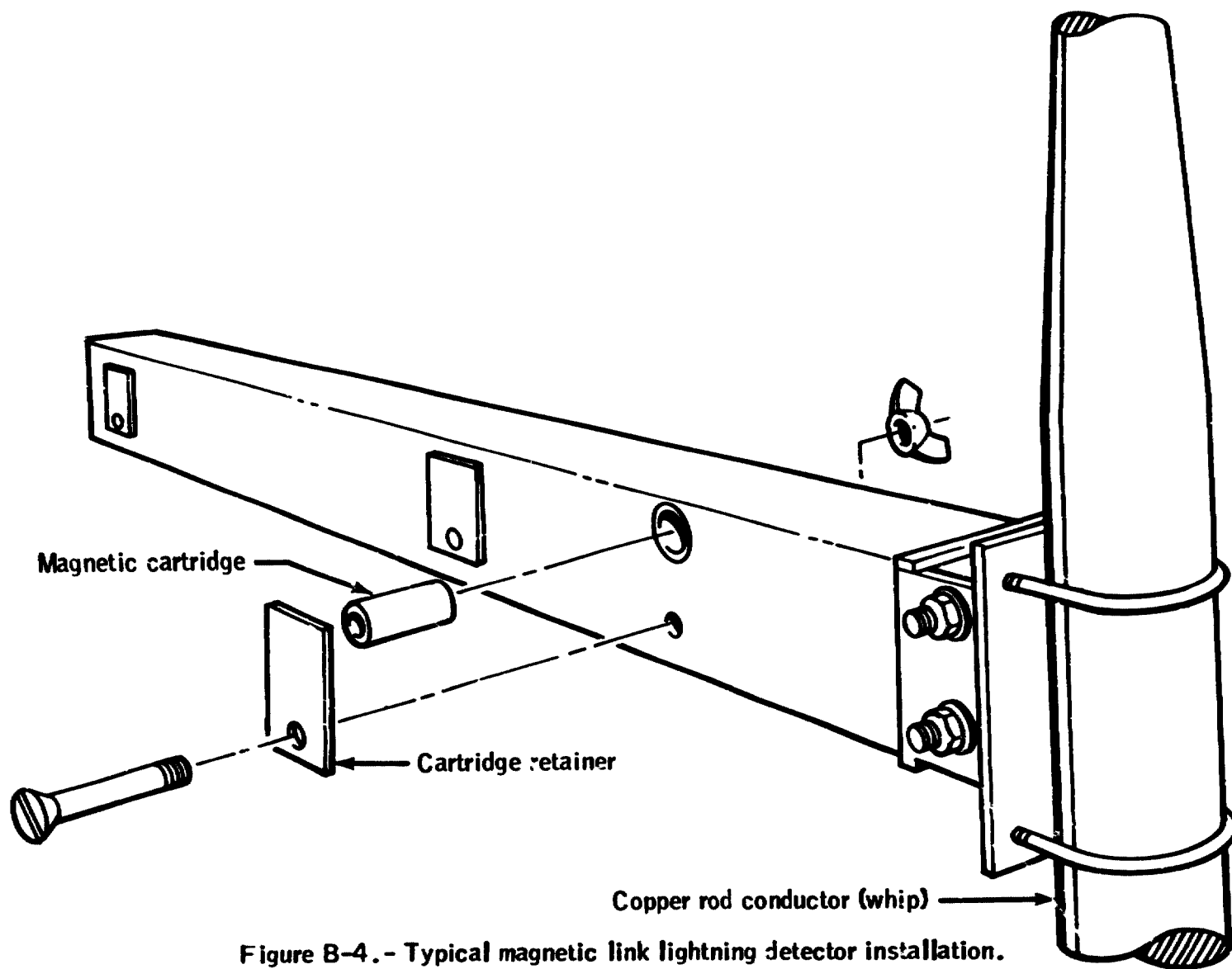


Figure B-4.- Typical magnetic link lightning detector installation.

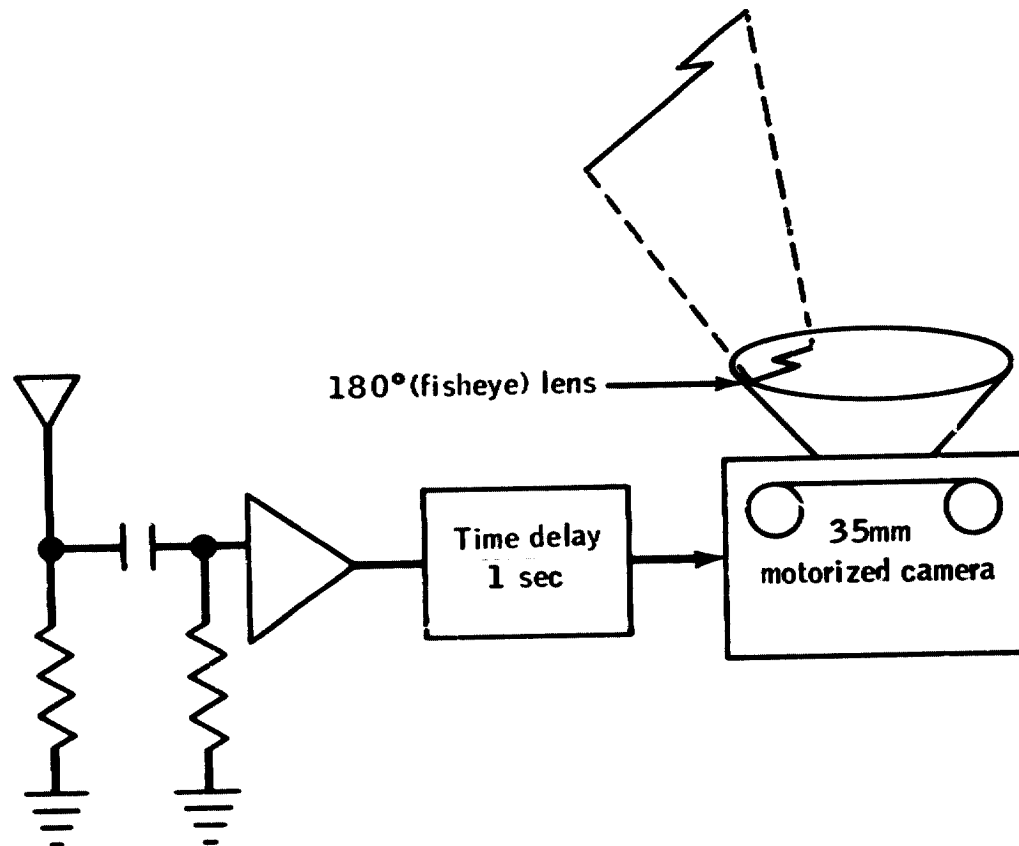


Figure B-5.- Automatic motorized camera.

To fully assess the damage to the vehicle and supporting ground equipment caused by a lightning strike to or near the launch facility, it is important to know the strike impact location, current waveshape, and peak magnitudes. The cameras provide a gross indication of the strike point. The readings obtained with the various magnetic links, while giving the peak currents, also help to locate the strike point. The memory voltmeters provide voltage levels on key spacecraft and ground equipment circuits from which the induction on other circuits is estimated. From the lightning waveform monitoring equipment, the current rate-of-rise is determined and is used to determine gross induction levels. These indications coupled with spacecraft and ground support system downlink telemetry measurements are used to determine if anomalous conditions exist in the spacecraft and ground equipment systems.

APPENDIX C

MEASUREMENT OF ELECTRIC FIELDS FROM AIRCRAFT

The airborne electric field meters that were available for the Apollo-Soyuz field measuring activity were of two basic types. Three aircraft were equipped with a cylindrical type that employed a rotating sense plate. The other five aircraft were equipped with a fixed-plate type with a grounded rotating shutter like the ground instruments described in appendix B. The airborne system discussed in this appendix used the fixed sense plate type.

The measurement of electric fields aloft is complicated by certain factors. The conductive surface of the aircraft distorts the ambient electric field such that its direction is normal to the aircraft surface (fig. C-1). This must be considered in the design of the measurement system so that the ambient field can be reconstructed from the field components measured at the surface of the aircraft. To do this, the Cartesian components of the ambient field are measured with three orthogonally oriented field meters. These are located such that each will respond strongly to one field component but will have a minimum response to the other two components (fig. C-2).

Another factor to be considered in the design of the airborne system is the electric field caused by the self charge of the aircraft. This field is superimposed upon the ambient field when measured at the aircraft surface. The effect is determined by measuring the aircraft potential with a fourth field meter and applying an enhancement factor. Thus, there are four quantities to be measured; the ambient field components E_x , E_y , E_z , and the potential, V_a , of the aircraft. Figure C-3 is a matrix describing the relationship of these four unknowns. The coefficients a, b, and c are constants associated with the location and orientation geometry of each field meter. The constant d is a factor indicating the relative enhancement of the measured electric field due to the self charge on the aircraft.

These constants are determined empirically by using a metallic model of the aircraft in an electrostatic cage (fig. C-4). Electrostatic probe measurements are taken while rotating the model in pitch, yaw and roll. These data are then used to determine the constants for the inverted matrix (fig. C-5) that gives the ambient field components and the aircraft self charge enhancement factor in terms of the field meter readings. This procedure thus calibrates the field meters to the aircraft.

In the airborne systems, the ambient field components are obtained by feeding the field sensor outputs to an electronic analog processor (fig. C-6). These quantities are then recorded on strip charts for future use. The outputs of the field sensors can be recorded before processing, if desired.

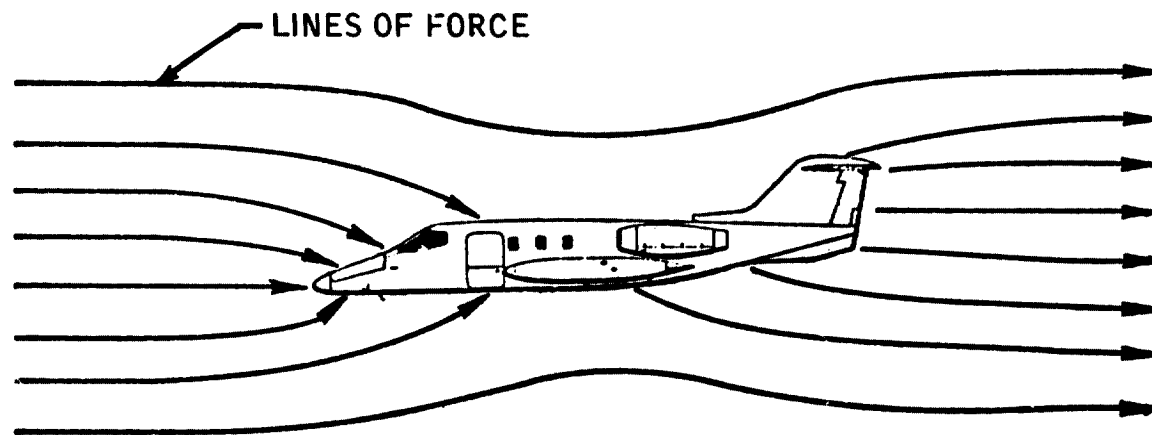


Figure C-1.- Distortion of uniform electric field caused by an aircraft.

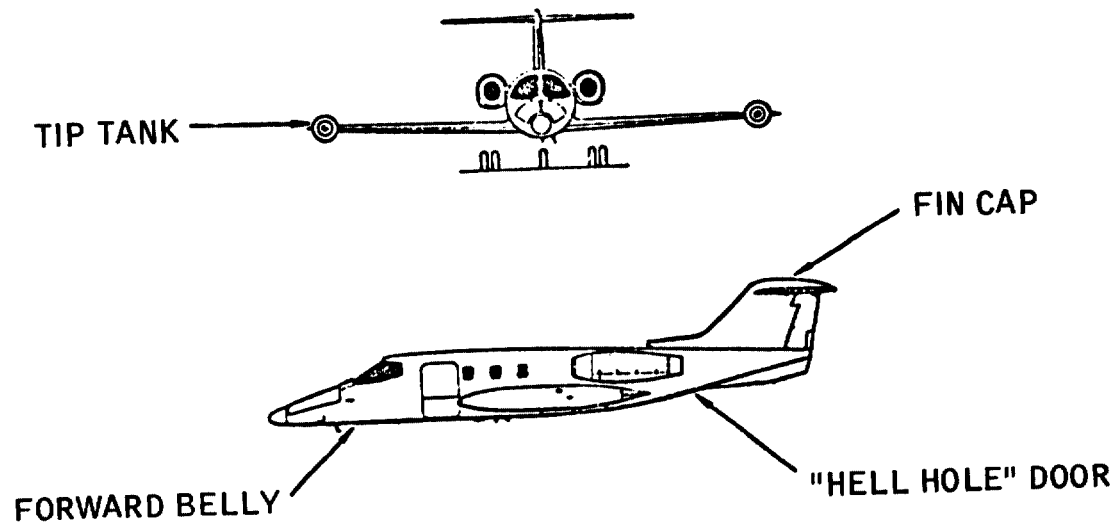


Figure C-2.- Location of field meter sensors on test aircraft.

$$\begin{aligned}E_{FIN} &+ a_1 E_x + b_1 E_y + c_1 E_z + d_1 V_a \\E_{AFT} &+ a_2 E_x + b_2 E_y + c_2 E_z + d_2 V_a \\E_{FWD} &+ a_3 E_x + b_3 E_y + c_3 E_z + d_3 V_a \\E_{WING} &+ a_4 E_x + b_4 E_y + c_4 E_z + d_4 V_a\end{aligned}$$

Figure C-3.- Matrix of field calibrations on test aircraft.

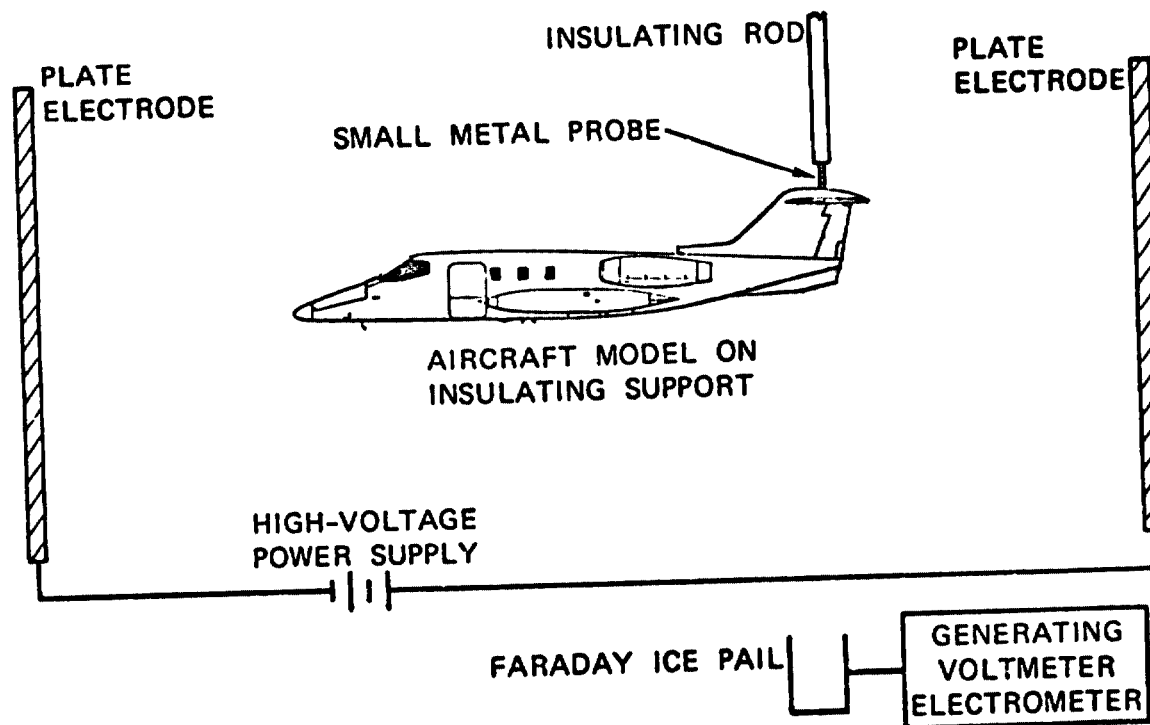


Figure C-4.- Electrostatic cage used for aircraft calibration.

$$E_x = 0.012 E_{FIN} - 0.52 E_{AFT} + 0.56 E_{FWD} + 0.00 E_{WING}$$

$$E_y = -0.14 E_{FIN} + 0.36 E_{AFT} - 0.63 E_{FWD} + 0.11 E_{WING}$$

$$E_z = 0.180 E_{FIN} - 0.48 E_{AFT} + 0.21 E_{FWD} + 0.00 E_{WING}$$

$$V_a = -1.15 E_{FIN} + 0.86 E_{AFT} - 3.10 E_{FWD} + 0.00 E_{WING}$$

Figure C-5.- Inverted matrix of aircraft field meter calibration.

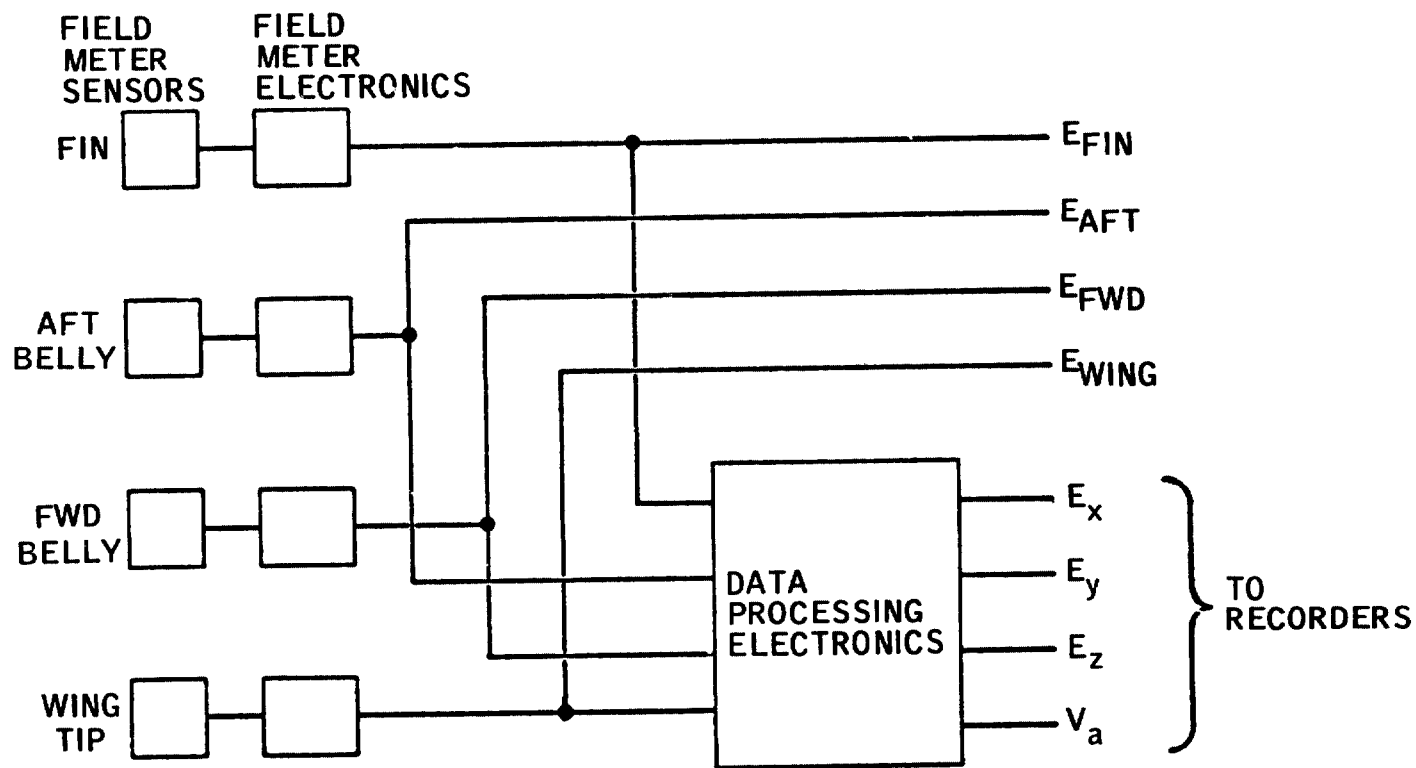


Figure C-6.- Block diagram of aircraft field measuring electronics.

The airborne system that has been discussed was used on the NASA Lear Jet for cloud electrification studies in the summer of 1975. The aircraft possessed some important characteristics (fig. C-7) that allowed an acquisition of unique data on the electrical properties of developing thunderstorms. Of particular importance was the service ceiling of 13.7 kilometers and the climb rate of 2073 meters per minute. These characteristics made possible the measurement of electric fields around the storm cell during development of the turret (main vertical body) and subsequent anvil.

Isolated storm cells were selected so that the measured electric fields would not be affected by nearby storms, to avoid unsafe flying conditions, and to insure a level flight attitude when taking data. The position of isolated cells could also be more readily fixed with ground-based radar when available. The aircraft was flown at various altitudes around the thunderstorm while recording electric field data. Several passes, with different headings, were flown for each altitude (fig. C-8).

The onboard weather radar provided an indication of the aircraft position relative to the cloud. During each pass the strip charts were annotated with time hacks indicating the start, midpoint, and end of the run. The aircraft position coordinates, airspeed, heading, altitude, and attitude (if not horizontal flight) were also noted. In addition, the unusually high field levels were flagged. These flags help to establish priorities for subsequent data reduction activity.

Postflight, the data were used to establish ground tracks from which the electric field vectors along the flight path of the aircraft could be ascertained. A summary of some of the data is shown in figure C-9. The electric field vectors that were calculated for two passes over an anvil at the 12.5-kilometer altitude is shown in figure C-10. It can be seen that charts such as this, showing the electric field vectors for each altitude, can provide a fairly complete description of the electric fields surrounding various cloud types.

From a limited analysis of the statistically small amount of data taken by the Lear Jet, an interesting observation is made. It appears that the high electric fields observed in the vicinity of anvils are most likely associated with charge concentrations in the thunderstorm main vertical body. Additional data and further analysis of existing data will be necessary to confirm that this is indeed the case.

SERVICE CEILING	13.7 km (45,000 ft)
CRUISING SPEED	239 meters/sec (464 knots)
RATE OF CLIMB	2073 meters/min (6800 ft/min)
ACCOMMODATIONS	Three passengers + instrumentation
CABIN PRESSURE	Sea level below 7010 meters (23,000 ft) aircraft altitude
CREW	Pilot, Copilot
CABIN ACOUSTIC NOISE	Low
VIBRATION LEVEL	Low

Figure C-7.- Some important characteristics of Lear Jet Aircraft.

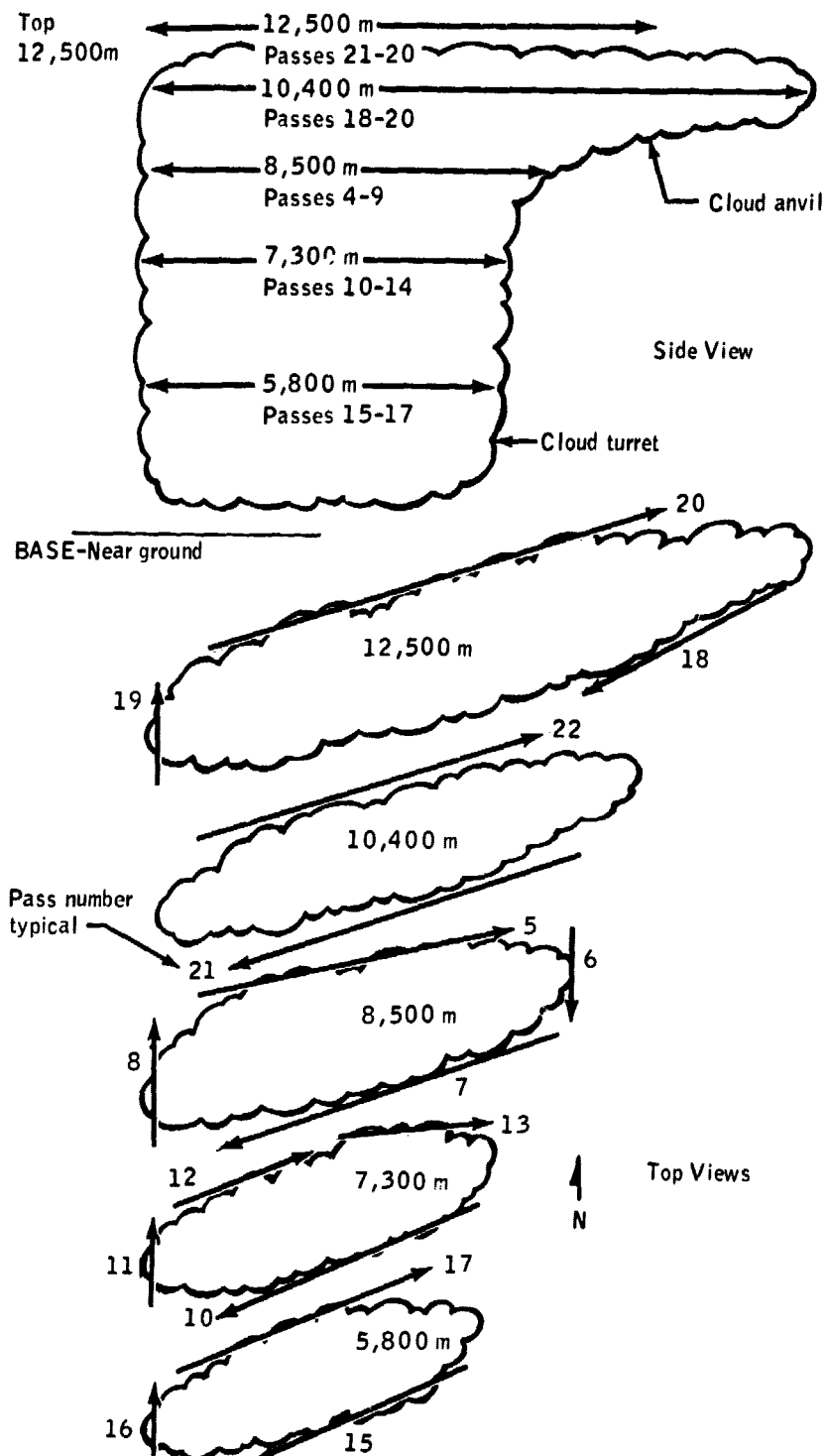
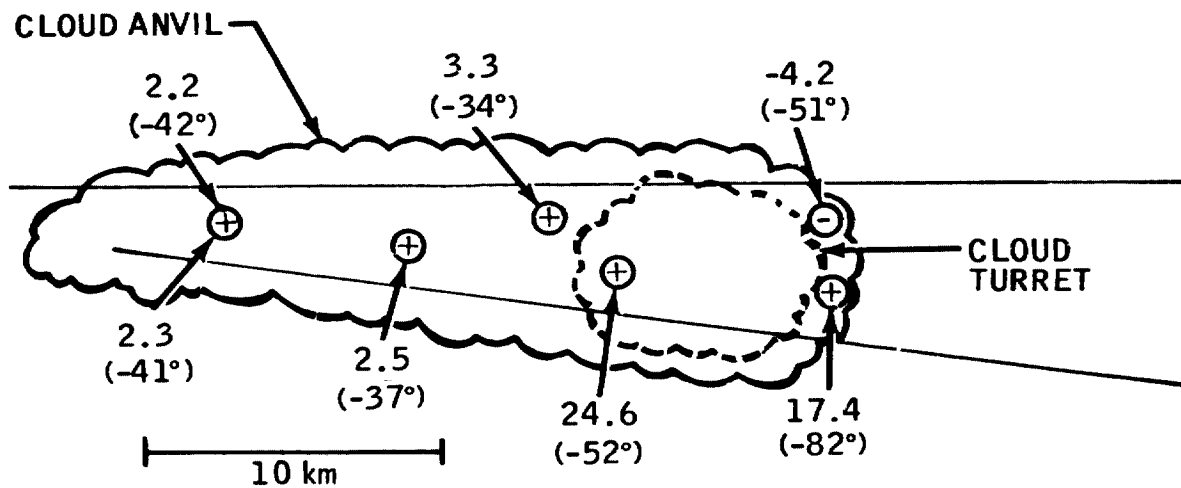


Figure C-8.- Flight path of aircraft around storm cell.

DATE	HEIGHT (km)	PASSES	MAXIMUM FIELD (kV/m)				COMMENT
			E	E _z	E _x	E _y	
7/17/75	9.1	1	Q-mill	-21	+29	-29	Building cloud; at anvil height
	10.1	1	Q-mill	-8	+10	-5	
7/21/75	8.8	3	47	+41	-23	-4	Under anvil
	10.4	3	33	-31	-6	-11	In anvil at times
	11.9	3	25	-21	-8	-11	Anvil middle
	13.1	3	17	-17	-1	+0.3	Near top of anvil
7/22/75	10.4	3	31	-30	+4	-8	Skirting anvil base
	12.5	2	38	-38	0	0	Over anvil top
7/22/75	12.5	2	3.4	-2	+2	-1.8	Data? (trapped charge) Over anvil top
7/25/75	5.5	2	2.7	+2	-1.4	+0.3	Building cloud with turret and anvil
7/26/75	4.9	2	15	+10	-11	+3	Under pseudo-anvil
	6.4	1	51	+50	0	-8.3	Thru side-pseudo anvil

Figure C-9.- Electric field levels in and around thunderstorm anvils.



Note.
 Top number is electric field
 vector magnitude in kilovolts/
 meter
 Number in parenthesis is the
 vector dip angle

Figure C-10.- Electric field vectors above an anvil at 12.5 km altitude.